Working Paper 3/2011

Wetter and Wilder: Impacts on the electricity industry in Western Europe of climate change

Rolf Golombek, Sverre A.C. Kittelsen and
Ingjerd Haddeland

The CREE Centre acknowledges financial support from The Research Council of Norway, University of Oslo and user partners.
ISBN: 978-82-7988-104-9
ISSN: 1892-9680
http://cree.uio.no

Wetter and Wilder: Impacts on the electricity industry in Western Europe of climate change

Rolf Golombek • Sverre A.C. Kittelsen • Ingjerd Haddeland

Abstract This paper studies some impacts of climate change on electricity markets, focusing on three climate effects. First, demand for electricity is affected because of changes in the temperature. Second, changes in precipitation and temperature have impact on supply of hydro electric production through a shift in inflow of water. Third, annual plant efficiency for thermal generation and nuclear will decrease because the temperature of water used to cool technical equipment increases. To find the magnitude of these partial effects, as well as the overall effects, on Western European energy markets, we use a modified version of the multi-market equilibrium model LIBEMOD. We find that each of the three partial effects changes the average electricity producer price by less than 2 percent, while the net effect is an increase in the average electricity producer price of only 1 percent. Similarly, the partial effects on total electricity supply are small, and the net effect is a decrease of 4 percent. The greatest effects are found for Nordic countries with a large market share for reservoir hydro. In these countries, annual production of electricity increases by 8 percent, reflecting more inflow of water, while net exports of electricity doubles. In addition, because of lower inflow of water in summer and higher in winter, the reservoir filling needed to transfer water from summer to winter is drastically reduced in the Nordic countries.

Keywords *Climate change; Electricity markets; Economic modelling; Inflow; Carnot effect.*

Acknowledgement: Earlier versions of this paper were presented at the national meeting for Norwegian economists, seminar for the Norwegian Ministry of Oil and Energy, and at the Nordic Energy, Environmental Constraints and Integration (NEECI) Workshop – we thank all participants for their comments. We will also thank Jennifer C. Adam at Washington State University for making the meteorological input data for the VIC model available. Research support from the Research Council of Norway under the program NORKLIMA is gratefully acknowledged. Parts of this research were undertaken in cooperation with the Global Water System Project (GWSP) and the European Union (FP6) funded Integrated Project WATCH (contract 036946). While carrying out this research we have been associated with CREE - Oslo Centre for Research on Environmentally friendly Energy. CREE is supported by the Research Council of Norway.

R. Golombek

Frisch Centre, Gaustadalléen 21, NO-0349 Oslo, Norway
e-mail: rolf.golombek@frisch.uio.no

S.A.C. Kittelsen (Corresponding author)

Frisch Centre, Gaustadalléen 21, NO-0349 Oslo, Norway
Phone: +47-22958815, Fax: +47-22958825
e-mail: sverre.kittelsen@frisch.uio.no

Ingjerd Haddeland

Norwegian Water Resources and Energy Directorate, P.O. Box 5091, Maj., NO-0301 Oslo, Norway

e-mail: iha@nve.no

1. Introduction

Climate change will have impact on supply of, and demand for, goods. For example, a change in temperature will shift demand for electricity based heating and cooling, thereby causing shifts in the equilibrium price and quantity of electricity. So far, this type of effect has received limited attention among economists, but see chapter 7 in IPCC (2007a) and Bosello et al. (2007).

In the economics climate change literature, the main focus has been to study the impacts of imposing efficient climate policy instruments, thereby giving agents incentives, in the short run, to relocate resources towards less GHG-intensive activities, and, in the long run, incentives to develop and use more climate-friendly technologies, see, for example the Stern review (2007). Whereas most economic studies focus on how climate policy leads to changes in demand and supply, the literature on the direct effects of climate change is more partial, typically overlooking that price and quantity will respond.

There are studies examining the impact of climate change on hydropower (e.g., Lehner et al. 2005; Hamlet et al. 2010; Madani and Lund 2010), on thermoelectric power generation (e.g., Forster and Lilliestam 2010) and on wind power (e.g., Sailor et al. 2008; Lucena et al. 2010). Shifts in each of these technologies will have impact on the equilibrium price of electricity, an issue that has typically been neglected. This was stressed in the Mideksa and Kalbekken 2010 literature review of on the impact of climate change on electricity markets; there is a lack of economic equilibrium modelling that takes account of supply and demand effects on electricity prices and quantities. The purpose of the present study is to fill some of this gap by examining direct effects of climate change on electricity markets in Western Europe, and the equilibrium consequences of these effects.

There are a number of direct effects of climate change on electricity markets in Western Europe. In the present study we focus on three of these, excluding factors like, for example, wind conditions and water availability for cooling of power plants. First, demand for electricity is affected because of temperature changes. Typically, warmer summers lead to increased demand for cooling, and thus more production of electricity, whereas higher temperatures in the winter decrease demand for electricity-based heating. Hence, both seasonal and annual demand for electricity change. While the sign of the change in seasonal demand is clear, it is an empirical question whether annual demand will increase or decrease in a country.

Second, for hydro electric power generation like reservoir hydro, changes in precipitation and temperature have impact on supply of electricity through a shift in inflow of water: both annual inflow and the distribution of inflow between summer and winter will change. These changes will have impact on hydro power production as well as on investments in reservoirs, and hence on the amount of water transferred between seasons.

Third, for thermal power generation including nuclear, average annual plant efficiency will decrease. These technologies use water to cool technical equipment, and hence higher water temperatures, reflecting higher average temperatures in the air, will lower energy efficiency – this is the so-called Carnot (1890) effect. In fact, in the summer water temperatures may occasionally be so high that nuclear plants have to stop operating.

The contribution of this article consists of three parts. First, we contribute to the literature on impacts of climate change on hydro power. Second, we bring together the best significant estimates of the (selected) three direct effects of climate change on electricity markets. Third, and most importantly, we modify a numerical economic equilibrium model for energy markets and use this to find the impact on electricity prices, production, storage and transmission of each direct climate change effect as well as the net equilibrium effect of *all* the three direct climate effects.

What are the equilibrium effects of climate change for the electricity industry? Whereas the summer demand effect (more cooling) suggests an increase in electricity production, the inflow summer effect (less applicable precipitation in most countries, see discussion below) and the plant efficiency effect (lower energy efficiency) have the opposite effect on supply of electricity. All three effects put, however, upward pressure on summer electricity prices. Similarly, the winter demand effect (less heating) and the plant efficiency effect tend to decrease winter production, whereas the inflow winter effect (more usable precipitation) has the opposite effect. The plant efficiency effect should imply higher winter prices, while lower winter prices should follow from reduced winter demand and increased winter inflow. The main purpose of the present study is to identify the magnitude of the three partial effects, as well as the overall effect of these three effects, on the Western European electricity market by applying and modifying the numerical multi-energy market model LIBEMOD.

The main focus of LIBEMOD is the Western European energy markets. In the model, agents in each Western European country determine investment, production, trade and consumption of energy goods; oil, natural gas, three types of coal, biomass and electricity. A key component of the model is electricity supply - in each country there are a number of different electricity technologies like gas power, coal power, nuclear, hydro and renewable. Profit-maximizing electricity producers determine investment in new production capacity as well as utilization of pre-existing capacities, facing technology specific constraints and a number of cost components; fuel cost, start-up cost, cost of maintaining the capacity and cost of expanding the capacity. LIBEMOD determines all prices and quantities in the energy markets.

LIBEMOD is suitable to examine the impact of climate effects on electricity markets. First, the model contains a detailed Constant Elasticity of Substitution (CES) demand system (see e.g. Perroni and Rutherford, 1995) which can be adjusted to account for changes in temperature. Second, because the modeling of hydro electric power specifies an inflow capacity of water, changes in precipitation are easy to implement in LIBEMOD. Third, the detailed modeling of electricity supply facilitates adjustments to capture the Carnot effect. In addition, LIBEMOD calculates the equilibrium effects on optimal investments and capacities in the power system. In particular, the model contains water reservoir capacities, and hence model runs provide information on the future optimal reservoirs size, thereby indicating the social optimal level of reservoir investment.

We find that each of the three partial effects changes the average electricity producer price in Western Europe by less than 2 percent. Because the partial effects are counteracting each other (see discussion above), the net effect is an increase in the average producer price of only 1 percent. Similarly, the partial effects on total electricity production in Western Europe are small, and the net effect is a decrease of 4 percent.

The greatest effects are found for Nordic countries with a large market share for reservoir hydro. Total annual production of electricity in the Nordic countries increases by 8 percent, reflecting more inflow of water. A substantial part of the increase in Nordic production is exported; climate change doubles net exports of electricity from the Nordic countries. With decreased domestic heating demand in winter, and higher inflow of water in winter, less water is transferred from summer to winter, and production of hydro in the summer increases significantly in the Nordic countries.

The rest of the paper is organized as follows. In Section 2 we discuss the direct effects of climate change on electricity markets. Section 3 provides a more detailed presentation of the numerical model LIBEMOD, while the results of this study are presented in Section 4. Section 5 summarizes our main results and points at topics for further research.

2. Climate change

The climatic effects of greenhouse gas emissions are primarily increases in temperature and changes in precipitation across the globe. The impact on wind is more uncertain. Pryor et al. (2005a) used a regional climate model for northern Europe. This study found small changes in wind speed between 2071-2100 and the control period. Kjellström et al. (2011) found that in Europe winds are generally expected to decrease. However, wind speed is projected to increase in the winter in parts of the northern ocean areas and in parts of the Mediterranean in the summer. Haugen and Iversen (2008) analysed an ensemble of eight projections for changes in wind conditions, using regional climate models. They found that for Northern and Central Europe, the changes in average wind conditions are minor, but there is a tendency for higher wind speeds.

The above mentioned studies tend to predict higher wind speed in the future, but this may not be so important because wind power stations cannot utilize very high wind speeds. However, the main lessons from the literature are that future wind conditions in Western Europe are uncertain, and that there are no consensus estimates for change in wind conditions that are significantly different from the no change scenario. Hence, inclusion of a change in wind conditions would only add uncertainty to our model. Therefore, we decided to disregard changes in wind conditions. Moreover, we believe the uncertainty about cost estimates for wind power may be so high that we cannot use LIBEMOD’s output with respect to wind power investments. Hence, in the present study wind power investments are exogenous.

The climatic effects we attempt to model below are:

a. changes in demand for electricity due to changes in the need for heating and cooling,
b. changes in supply of hydropower due to changes in precipitation and temperature, and
c. changes in thermal power supply due to warmer cooling water (reflecting higher air temperature) and therefore lower plant efficiency.

Emissions of greenhouse gases have major damaging effects in the long run, while the short-run effects are minor. Typically, the impact of emissions over a few decades can hardly be distinguished from the natural variation in the climate system. This suggests focusing attention on a year several decades ahead when examining the impact of climate change on electricity markets, for example, 2100. On the other hand, not much is known about the energy markets in 2100, for example, what will be the cost efficient technologies in 2100? Probably, technologies developed as a response to climate change will be much more efficient and have lower carbon emission intensities than the current state-of-the art technologies. The dominant position of fossil-fuel based electricity plants may continue for some decades, but plants may have integrated carbon capture facilities. Later, fossil fuel based technologies may be replaced by technologies based on wind, solar and waves; these are emission free and may also lead to reduced demand for transmission and distribution of energy. The bottom line is that we simply do not know much about energy markets in 2100.

There is no obvious solution to the trade-off between, on the one hand, focusing on a year sufficiently far ahead to capture significant climate change effects, and, on the other hand, examining a year which reasonably can be regarded as a continuation of the present structure and historical trend of the energy markets. In order to illustrate the impact of climate change on electricity markets, below we use a pedagogical tool, namely to postulate that the average climate in a future time period (2070-2099) materializes in a much earlier year (2030). The year 2030 is long enough into the future to enable optimal investments to change production and transport capacities, but short enough that the economic and political structure can reasonably be expected to continue on the historical trends presently observed. The resulting scenarios and simulations must therefore be carefully interpreted; they are not predictions of actual behavior, but are comparative static simulations of the effects of a climate change on a power system that has had time to adapt.

Below, climate change effects for 2070-2099, for simplicity referred to as 2085, build on the IPCC scenario A1b, see IPCC (2007). This is the most referred emission scenario of IPCC (2007b), with a projected global warming of 2.8 ºC until the end of this century. While IPCC (2007b) reports results from global climate model simulations, these must be disaggregated to find climate effects for each Western European country, which is needed in our analysis. Downscaling of temperature was performed using an empirical-statistical method based on climate model results, ERA40 re-analysis data, see Uppala et al. (2005), and weather station observations, see Benestad (2005) and Benestad (2008a). The downscaling was based on 20 global climate models described in the IPCC fourth assessment report (Meehl et al., 2007). Some of the GCMs have been used to make several parallel runs; these differ by their initial conditions (starting point). The estimated multi-model mean temperatures for the period 2071-2100 were used. The complete list of the global circulation models and runs included in this analysis can be found in Table 5 in Benestad (2008b).

2.1 Demand for electricity

The demand effect of a warmer climate operates primarily through the need for increased cooling during the summer, and less heating during the winter. In the literature, these effects are picked up by the annual number of Cooling-Degree-Days (CDD) and Heating-Degree-Days (HDD): Let T_d be the average daily temperature measured in Celsius on day *d*. Then $T_d - 22$ (if positive) is the number of degrees that the average temperature exceeds 22 ºC on day *d*. When this (positive) number is summed over all days in a year for which T_d exceeds 22 ºC, one obtains CDD; $\sum_{d=1}^{365} \text{Max}(0, T_d - 22)$. HDD is the corresponding sum of temperatures lower than 18 ºC; $\sum_{d=1}^{365} \text{Max}(0, 18 - T_d)$.

What does the literature tell us about the heating and cooling effects of climate change? According to the Mideksa and Kalbekken (2010) review, the sign of the heating and cooling effects on electricity demand seem to be consistent across studies, but with a wide variation on the magnitude of the estimates. In an early study for California, Baxter and Calandri (1992) found moderate effects on demand; a 1.9 ºC higher temperature increases demand for electricity by (up to) 2.6 percent. Aroonruengsawat and Auffhammer (2009) used micro data to estimate demand response functions in 16 California climate zones. They claim to find higher projected impacts than in other studies.

Using a global model, Isaac and van Vuuren (2009) projected a 34 percent decrease in residential heating energy use and a 72 percent increase in cooling energy use by 2100 if temperatures increase by 3.7 ºC, but this is not directly transferrable to electricity demand. De Cian et al. (2007) estimated the temperature dependency of energy demand from a panel of 31 developed countries. They found that an increase in temperature increases demand in warm countries and reduces demand in cold countries. Their estimation does not take account of the endogeneity of prices, and the results can therefore be confounded by supply effects.

Our preferred source is Eskeland and Mideksa (2009), which used an instrumental variables approach to account for the endogeneity of prices. This is an econometric study of residential demand for electricity using a panel of Western European countries. Using a fixed-effects regression model, this study allows for country differences in the response to temperature changes. As is common in the literature, they include the annual number of Cooling-Degree-Days and Heating-Degree-Days among the independent variables. Their estimates of the effect of CDD and HDD on per capita electricity consumption are small but significant.

The Eskeland and Mideksa study has also calculated CDD and HDD separately for 2000 and 2085 for each Western European country based on city-specific data in Benestad (2008a)[1]. They found that the climate change from 2000 to 2085 increases CDD by 121 (88 percent) and decreases HDD by 712 (28 percent) for Western Europe as a whole, see Table A.1 in Appendix A for country effects.[2]

Combining the estimated coefficients of CDD and HDD (from a historic panel) from Eskeland and Mideksa (2009) with the calculated changes in CDD and HDD because of climate change from 2000 to 2085, we find that, cet. par., demand for electricity in Western

[1] Benestad (2008a) actually compares the current ”normal” climate, defined as the average over the period 1961-1990, to the average over the predictions for the years 2070-2099. For brevity we will refer to these as 2000 and 2085 climate respectively.

[2] Hamlet et al. (2010) finds a reduction in HDD for the Pacific Northwest. However, this study argues that because of population growth demand for heating energy will increase.

Europe increases from 2000 to 2085 due to increased cooling needs by 3.6 percent, but decreases due to lower heating needs by 7.3 percent. The net direct effect on demand, before the feedback from the model equilibrium changes of supply and prices, is a decrease in annual demand in Western Europe by 3.7 percent due to the climate change from 2000 to 2085.

Figure 1 shows electricity demand in the base year 2000 and calculated direct changes in demand with 2085 climate because of more cooling and less heating. As seen from the figure, demand changes are not uniform across countries. As expected, the Northern European countries decrease their heating demand, but there is almost no increase in their cooling demand since even with a warmer climate there are few days with an average temperature above 22 ºC. This is mostly reversed in Southern European countries where the increase in cooling demand clearly dominates over the decrease in heating demand. Because heating mainly is needed in winter and cooling mainly in summer, these demand changes are imposed on the demand system of LIBEMOD in the corresponding season only. The effect of climate change on demand in the model is a shift from northern to southern countries, and a shift from winter to summer.

2.2 Inflow of water

Projected changes in runoff have been estimated by the VIC macro scale hydrology model (Liang et al. 1994). The model was run at 0.5 degree spatial resolution for the baseline period (1961-1990), using CRU (Climate Research Unit of the University of East Anglia) meteorological input data (Mitchell and Jones 2005). For the projection period (2070-2099), air temperature and precipitation data from two global circulation models (GCM) run under the A1b emission scenario were used.[3] The first GCM projection applied here was calculated by the Hadley Center Coupled Model (HadCM3, Gordon et al. 2000), whereas the second data set results from the Max Planck Institute model ECHAM5 (Roeckner et al. 2006). To create the meteorological input data the 'delta change approach' was used: the monthly changes in precipitation and temperature between baseline and projection were calculated,

[3] Estimates of future climate variables, e.g. precipitation and temperature, vary somewhat between global climate models, thereby leading to slightly different simulation results when using future estimates as drivers in hydrological models. It is not known which global climate model that gives the best estimate. Therefore, we opted to use information from two global climate models, Echam and Hadley, and used the average of the two runs in the LIBEMOD model simulations.

and these changes were imposed on the CRU data. The meteorological data for the baseline and the projection periods were created similarly to the method used by Adam et al. (2009). The results for each run are given as a percentage change in runoff between baseline and future periods for each country and for the summer (April 1 – September 30) and winter (October 1 – March 30) seasons. These seasonal changes in runoff differ from projected changes in precipitation because of changes in evapotranspiration, and they also reflect future changes in snow accumulation and melting.

In hydropower production, runoff is only useable to the extent that it reaches run-of-river power plants or the reservoirs; in the latter case the energy content depends on the altitude difference between reservoir and power station. In LIBEMOD, inflow, which differs by country and season, measures the energy content of usable water (TWh). For Norway, a detailed model of the power system ("samkjøringsmodellen") has been used to calculate seasonal inflow that would result from the 2085 runoffs while keeping the 2000 power system infrastructure. For other countries we have assumed that changes in inflow are proportional to country-average changes in runoff in each season.

Figure 2 shows inflow in 2000 and 2085 by country and season, where the 2085 numbers reflect the direct effect of climatic change, and the hydropower capacities are kept unchanged from 2000. Norway is clearly the biggest producer of hydropower, but several other countries also have sizeable hydropower sectors. According to Figure 2, annual inflow in Sweden, Finland and Norway increases, whereas there is a decline in Southern European countries. The net effect is a 15 percent decrease in inflow (and thereby production) for the group of model countries. Note that in a deterministic model such as LIBEMOD, spillage of water is never optimal and annual inflow is equal to annual hydropower production.

In the Nordic and Alpine countries most of the inflow is received in the summer, because winter precipitation falls as snow in the winter and is only usable for electricity production when it melts the following summer. These countries all expect an increase in winter inflow in 2085, mostly due to higher temperatures. In Southern Europe, summer inflow decreases as a result of both lower precipitation values and higher temperatures. The main pattern is a shift in inflow from Southern to Northern Europe, and from summer to winter, exactly mirroring the demand changes.[4]

2.3 The Carnot effect

The efficiency of thermal power plants depends on the temperature of the water used for cooling; the hotter the water, the lower is efficiency. Atmospheric warming and changes in river flow are expected to affect river temperatures. For example, Mohseni et al. (1999) and Mantua et al. (2010) both conclude that river temperatures are likely to increase because of climate change. van Vliet et al. (2011) examines how the critical water temperature limit of 23 °C for intake of cooling water is affected by climate change. They found that for the Rhine at Lobith, the mean number of days per year that exceeds the critical temperature limit increases from 16 in the reference period (1980-1999) to 47 if the air temperature rises by 4 ºC.

The thermal efficiency of power plants that need cooling is in theory linearly dependent on the temperature of the cooling water or cooling air, and thus the average efficiency of thermal plants will be reduced because of climate change – this is usually referred to as the Carnot effect. Under intense heat waves, nuclear plants may even need to close for safety reasons, this happened in France, Germany and Spain in 2006, and later in Sweden. Below, the Carnot effect means that for *the same* amount of inputs, output is reduced. However, the Carnot effect will in general lead to a change in the amount of inputs through the market mechanism.

If a plant has full capacity utilization prior to the Carnot effect, output will for sure decrease because of the Carnot effect. In general, the Carnot effect means that each level of output has become more expensive to produce, and hence the marginal cost curves of power producers shift upwards. If, like in LIBEMOD, producers are small and maximize profits, this means that the aggregate supply curve of electricity producers shifts upwards. Then we know from standard economic theory that the price of electricity will increase, whereas aggregate output will decrease.

---

[4] Our results are similar to those of Lehner et al. (2005). They find that by the end of the century the hydropower potential in southern Europe may decrease by at least 25 percent, whereas the hydropower potential in northern Europe may increase by at least 25 percent.

The first step in identifying the Carnot effect is to estimate the temperature changes. Benestad (2009) has estimates for 2085 quarterly temperatures for the same cities as in Benestad (2008a). We have aggregated these to the seasons and countries in LIBEMOD; we find that the average 2085 temperature (relative to 2000) increases by 3.0 ºC in summer and 2.8 ºC in winter.

The Mideksa and Kalbekken literature review found few studies on quantifying the effect of temperature increase on thermal power efficiency. Yet, some studies are available, for example, Durmayaz and Sogut (2006) found that a 1 ºC increase in the temperature reduces nuclear power output by about 0.45 percentage points. Linnerud et al. (2009) estimated the Carnot effect on a panel of monthly temperature and production data for European countries. They found that thermal efficiency in fossil fuel based plants decreases by 0.6 percent (not percentage points) for each degree Celsius increase in temperature, while in nuclear power plants it decreases by 0.8 percent per degree Celsius increase in temperature. Finally, Linnerud et al. (2011) estimate the Carnot effect for nuclear power plants, obtaining somewhat lower effects than those in Linnerud et al. (2009).

Building on Durmayaz and Sogut (2006), Linnerud et al. (2009) and Linnerud et al. (2011), and taking into account that the effect on productivity is not linear in temperature change, we obtain that thermal efficiency in 2085 is reduced by 1.8 (1.7) percent in summer (winter) in fossil plants, and by 2.4 (2.3) percent in nuclear plants. Because plant efficiency differs in our numerical model LIBEMOD, the Carnot effect will be (slightly) different across technologies and countries. Note that the Carnot estimates are uncertain. They have been estimated on small samples (this is in particular the case for fossil fuel plants), and adaptation strategies of power producers, for example, installing water pumps or relocate, have not been taken into account. Still, we believe the Carnot effect should be included in the analysis.

What is the direct impact of the Carnot effect of the 2085 climate, keeping the fuel use constant at year 2000 level? In the winter, the temperature increases are greatest in Northern Europe, for example, 4.9 ºC in Finland versus 2.4 ºC in Italy, see Figure 3, suggesting that the supply reduction is greatest in Northern Europe. Summer temperature differences are smaller, ranging from 2.4 ºC in Great Britain to 3.7 ºC in Spain, and hence the shifts in summer supply do not differ that much between countries. On the other hand, because fossil plants are less common in Northern Europe, there is a small tendency that, cet. par., the supply reduction as a share of total electricity supply is smallest in the north. Overall, the unambiguous effect is to reduce supply of electricity, while geographical and seasonal patterns are weak.

3. LIBEMOD

We use the numerical model LIBEMOD to find the equilibrium consequences of the three direct effects of climate change on electricity markets. LIBEMOD is an economic simulation model of the Western European energy industry, see Aune et al. (2008). Its main focus is on the electricity and natural gas markets in Western Europe, but it also covers global markets for coal and oil. The model distinguishes between model countries – each of 16 Western European countries – and exogenous countries/regions, the latter group contains all countries in the world outside Western Europe.

In each model country there is production of energy, trade in energy and consumption of energy, as well as investments in energy infrastructure. LIBEMOD has seven energy goods - coking coal, steam coal, lignite, natural gas, oil, biomass and electricity. While all markets are competitive, the number of countries participating in trade of energy goods varies. Natural gas and electricity are traded between model countries, and also a few exogenous countries, for example, Russia, trade in these two markets. Coking coal, steam coal and oil are traded in global markets, whereas lignite and biomass are traded in domestic markets only.

Production of energy takes place in all countries. Typically, in a model country there is extraction of some fossil fuels, production of bio mass and production of electricity (see detailed description below). Non-model countries/regions typically extract coking coal, steam coal and oil, and trade these in the global markets. Trade in natural gas/electricity requires gas pipes/electricity lines running between countries taking part in this trade. At each point in time, the capacities of these pipes/lines are given, but they can be expanded through investment. For a given international transmission capacity, all arbitrage profits in international natural gas and electricity trade is exhausted in LIBEMOD. Finally, there are losses related to international transmission of natural gas and electricity, and these losses are increasing in the amount of export.

In each model country energy is transported and distributed to the users at costs that differ according to user group and energy good. There are four groups of users of energy; power producers, households (including services), industry and transport. The first group represents intermediate demand; thermal power producers demand a fuel as an input in production of electricity. This fuel could be steam coal, lignite, natural gas, oil or biomass. The three latter groups represent end-user demand. While demand from transport is restricted to oil, the other end-user sectors typically demand several of the seven energy goods.

For end users, demand is derived from a nested CES utility function with five levels. These nests describe (i) substitution possibilities between energy-related goods and other forms of consumption, (ii) trade-offs between consumption based on different energy sources, and (iii) complementarity between the actual energy source and consumption goods that use this energy source (for example, electricity and light bulbs). In addition, for electricity the model describes substitution possibilities between summer and winter (season) and between day and night. The CES demand system has been adjusted to account for the demand effects of climate change, see Section 2.1.

LIBEMOD offers a detailed description of production of electricity. In general, there are a number of technologies available for production of electricity: steam coal power, lignite power, gas power, oil power, reservoir hydro power, run-of-river hydro power, pumped storage power, nuclear, waste power, biomass power and wind power. Base year capacities (from 2000) are depreciated over time, but if profitable there will be investments in new production capacities. In general, not all technologies are available in every country.

For each type of technology and country, efficiency typically varies across power plants. In particular, the distributions of efficiencies reflect the Carnot effect, see Section 2.3. There are four types of costs in electricity production: fuel costs (not relevant for hydro), maintenance costs (related to the share of the installed capacity that is maintained), start-up costs (related to additional capacity started in a time period) and investment costs. The power producer obtains revenues either from using (part of) the maintained power capacity to produce and sell electricity, or by selling the remaining part of the maintained power capacity to a national system operator, who buys reserve power capacity in order to ensure (if necessary) that the national electricity system does not break down.

Several of the cost elements are linked to capacities and technical constraints faced by power producers. Some of these are common for all electricity technologies, while others are technology specific. There are three technology-specific capacities for reservoir hydro; inflow capacity (collecting water in a "catchment" area and transporting the water to the reservoir), reservoir storage capacity and electricity generation capacity (maximum instantaneous production of electricity). For reservoir hydro the technical constraints are:

- The capacity that a producer chooses to maintain cannot exceed the installed capacity.
- A producer can sell a share of the maintained power capacity to the system operator.
- Power plants need some downtime for technical maintenance. Because this is an annual constraint, the producer may choose in which period(s) technical maintenance will take place.
- Start-up and ramping-up costs are incurred if electricity production varies between periods in the same season. These costs depend on the additional capacity started at the beginning of each period; that is, on the difference between capacity use in one period and capacity use in the other period during the same season.
- Total use of water – that is, total production of reservoir hydropower in a season plus the reservoir filling at the end of that season - should not exceed total availability of water – that is, the sum of the reservoir filling at the end of the previous season and the seasonal inflow of water. As explained in Section 2, inflows have been adjusted to capture climate change effects.
- Reservoir filling at the end of each season must at least be zero but cannot exceed reservoir capacity.

An electricity producer maximizes profits subject to the technical constraints. This leads to operating rules, as well as a decision rule for optimal investment, see Aune et al. (2008). The main exception from these rules is wind power; in the present study we assume that the wind power capacity in each country is given. Then wind conditions, which differ over the day, over the season, across countries and also within a country, determine supply of electricity.

LIBEMOD determines all energy quantities – investment, production, trade and consumption – and all prices for all energy goods (all fossil fuels, electricity and biomass), both producer prices and end-user prices. In addition, the model calculates emissions of carbon by sectors and countries.

LIBEMOD has been calibrated to the data year 2000, imposing that the parameters should reproduce observed demand, costs and efficiency distributions in 2000. For the CES utility functions (one for each type of end-user in each model country), the share and distribution parameters are calibrated to minimize the deviation from exogenous own-price and cross-price demand elasticities. For households, the own-price elasticities are in the range of -0.4 to -0.6, whereas for industry the range runs from -0.6 to -0.8. Note that demand elasticities vary slightly between the calibration equilibrium and each of the 2030 equilibria studied in Section 4. For each model country there is a load curve with four segments – one for each time period. According to our data, demand is typically higher in winter than in summer (heating requires more energy than cooling), and higher during the day than at night.

In addition to elasticity estimates and calibration values for the year 2000, the simulations for 2030 are based on assumptions about future conditions such as fuel efficiency in electricity productions, supply curves for oil, coal and gas extraction, and economic growth. These are mainly taken from IMF and OECD projections (e.g. Consensus Economics, 2007)[5]. For a more detailed description of LIBEMOD, including data sources, see Aune et al. (2008).[6]

4. Results

In the section we examine the long-run impacts of the three partial climate effects; changes in demand for electricity, supply of hydro and plant efficiency for thermal and nuclear power.

---

[5] In the light of the financial crisis of 2008-2009, the GDP projections might be viewed as optimistic, but are well within the uncertainty of such projections and by current estimates the same GDP levels would occur 4-8 years later.

[6] The version of LIBEMOD used in the present paper differs somewhat from the one documented in Aune et al. (2008), the main differences being i) electricity is traded in two periods over the 24-hour cycle (six periods in Aune et al. (2008)), ii) we use a more aggregated representation of coal markets, and iii) exogenous (not model determined) wind power capacities. We do not expect any of the differences between the two model versions to have (significant) impact on the results of the present paper.

We focus on the year 2030, assuming that the climate in 2030 equals the (average) climate predictions for the period 2070-2099, see the discussion in Section 2.

4.1 Base year climate

Both prior to imposing the climate change effects in 2030 and after these effects have been imposed, we assume that all model countries have a climate policy, here specified as a uniform price of CO2 of USD 50. This may be interpreted as a common carbon tax being imposed in all model countries, or the effect of an efficient cap-and-trade scheme covering all sectors in all model countries with an equilibrium price of tradable quotas at USD 50.[7] Of course, the partial effect of imposing such a carbon price - prior to imposing climate change - is to reduce carbon emissions in 2030 (by 28 percent among the model countries), mainly through decreased use of coal in coal-fired power plants (by 61 percent among the model countries). Increased costs of using fossil fuels raise electricity prices significantly, for example, the average price received by electricity producers in the model countries at the plant site - henceforth referred to as the producer price – increases by as much as 75 percent.

4.2 Price effects

In Figure 4, for each group of (five) bars the bar most to the left shows the change in producer price of electricity before we impose climate change effects ("Base year climate"), but after a carbon price of USD 50 has been imposed. For a given carbon price of USD 50, the second bar from the left shows the pure demand effect, the third bar from the left shows the pure inflow effect, the fourth bar from the left shows the Carnot effect, and finally the bar most to the right shows the *total* effect on the producer price of all three climate effects.

The first group of bars shows the effect for Western Europe, whereas the other groups show the effects for selected Western European countries. According to Figure 4, the total effect of a change in climate on the producer price in Western Europe is an increase of only 1 percent (For country-specific producer price and quantity effects, see Table A.2 in Appendix A). This average annual increase reflects that the average producer price on winter days has not

[7] In choosing a carbon tax we have balanced two concerns. First, according to IEA (2008), a tax in 2030 at almost USD 100 will be sufficient to stabilize global GHG concentrations in the atmosphere at 550 ppm. On the other hand, climate policy experts are typically pessimistic about the chance of sufficiently carbon policies being imposed, see, for example, Røgeberg et al. (2010). Here, we assume that half of the necessary tax is imposed.

changed, whereas the average price on winter nights, summer days and summer nights all increase by 2 percent. For each model country, the average annual producer price of electricity increases by either 1 or 2 percent. Hence, the overall price effect of climate change is negligible.

As mention in Section 3, in LIBEMOD electricity is traded in four time periods over the year. The price of electricity varies between these time periods (and also between countries). A natural question is then how the peak price of electricity responds to climate change; is the change in peak price significantly greater than the change in average price? The answer is no – also peak prices do not change much due to climate change. In order to obtain large peak-price changes, it is necessary to have many more periods over the year than four. For example, in Aune et al. (2008) we use a variant of LIBEMOD with 12 time periods over the year. But even with 12 time periods the modelling of peak demand is too rough to pick up significant variation in the price over the 24-hour cycle.

We now turn to each of the three partial effects. The demand effect – higher demand in the summer due to more cooling and less demand in the winter because of less heating – has negligible effects on the seasonal day/night prices: the average winter day price decreases by only 1 percent, while the three other average seasonal day/night prices change even less. The supply effect of changes in inflow of water to hydroelectric production changes the average seasonal day/night prices by less than 1 percent. This result mainly reflects that hydro has a small average market share (11 percent) in the model countries. Finally, the Carnot effect raises all average seasonal day/night prices by 2 percent, reflecting that on the one hand, a substantial share of the electricity production capacity is affected, but on the other hand, the change in plant efficiency is small.

4.3 Quantity results

As a result of *all* three direct climatic effects, total production of electricity in the model countries decreases by 4 percent, mainly reflecting the demand effect, see Figure 4. The inflow effect hardly changes total production of electricity, whereas the Carnot effect decreases total electricity production by only 1 percent, mainly reflecting lower production of gas power and nuclear.

As seen from Figure 5, the total effect on electricity production differs between countries. In Germany production decreases significantly, in Sweden production is roughly unchanged, whereas production increases in Italy and Norway. There are several reasons for why the climate change effects differ across countries. First, shifts in seasonal demand differ between countries, reflecting, for example, that in some countries there is no need for cooling because it never gets hot in the summer. Second, there are countries where a substantial share of the heating is based on electricity, for example, Norway, whereas in most other countries, for example, the UK, fossil fuels have a large market share in heat production.

An additional reason for country differences in the response to climate change is that the mix of electricity technologies differs, see Appendix A for details. In most Western European countries, fossil-fuel based electricity production and nuclear power cover most of the electricity generation. Yet, in some countries, particularly Norway, but also Sweden and to some extent Austria, Finland and Switzerland, hydro has a substantial market share, and hence in these countries the inflow effect is important, while the Carnot effect may not be that important. To take one example, total hydropower production decreases by 16 percent because of lower annual inflow in the model countries, and the inflow effect also changes the composition of supply between countries – in the Nordic countries production of hydro increases by 8 percent, whereas in most other countries hydro electric production decreases because of the inflow effect.

4.4 Trade effects

Because the impacts on electricity prices differ across countries, there is potential for more trade in electricity. Electricity will be exported from high price countries to low price countries if the price differential exceeds cost of transmission, subject to transmission capacity being available. For significant price differences between countries, expansion of international transmission capacity becomes profitable, which will increase international trade and lower the international price differentials. Hence, international trade may be of significant importance in determining price and quantity effects of climate change.

In our study the reported effects on electricity production are in general small, and hence trade does not change much. There is, however, a significant effect on electricity trade in Northern Europe: Without climate change, all Nordic countries are net exporters of electricity, and net exports from the Nordic countries are almost 50 TWh, which corresponds to roughly 10 percent of Nordic electricity supply. With all climate effects, Nordic net export doubles, reflecting that the electricity transmission capacity at the border of the Nordic countries and continental Europe has increased by around 80 percent, mainly due to the demand effect (60 percent), but to some extent also due to the inflow effect (20 percent), see Figure 6, panel a. In LIBEMOD, only profitable investments are undertaken, and hence expansion of the transmission capacity reflects significant price differentials between exporting and importing countries prior to investments in transmission.

The increase in electricity trade reflects that climate effects differ between the Nordic countries and continental Europe. In the Nordic countries, particularly Norway, but also Sweden, reservoir hydro has a substantial market share. Typically, the reservoir is used to transfer water from summer to winter, that is, water in the reservoir is scarcer in the winter than in the summer. In the Nordic countries, winter inflow of water increases substantially, summer demand does not increase much because cooling is hardly an issue, and winter demand decreases. These factors imply that less water is transferred from summer to winter in the Nordic countries, see Figure 6, panel b, while more electricity is exported from the Nordic countries in summer to satisfy increased cooling demand in Continental Europe. Hence, in the Nordic countries a smaller share of the reservoir is utilized. With less transfer of water from summer to winter, production of hydro in the Nordic countries increases in the summer (by 19 percent), whereas there is a minor decrease in winter hydro production (by 2 percent).

As discussed above, part of the increased electricity production in the Nordic countries is exported, which requires investment in international electricity lines. So far we have assumed that international electricity transmission capacities are determined through profitable investments. We now examine the importance of these investments. To this end, we fix all electricity transmission capacities at their *2030 equilibrium values* prior to climate change being imposed.[8] Under this restriction, the average electricity producer price increases by 0.3 percent because of the three climate effects, while with model determined capacities the increase was 1.4 percent. In most countries, there is hardly any difference between the national producer price with and without model determined capacities.

[8] Like in the other scenarios, investments in new power plants and in international gas pipes are determined in the model.

There are some exceptions from this rule, namely the Nordic countries. In these countries, the average electricity producer price increased by around 1 percent under model determined capacities. With fixed transmission capacities, the producer price decreases by 33 percent, 8 percent and 4 percent in Norway, Sweden and Finland, respectively. These differences reflect increased production of hydro because of more precipitation and less heating demand, see discussion above, which pushes down domestic electricity prices when there is no spare transmission capacity for export of electricity.

5. Conclusions

In the LIBEMOD model of the energy markets of Western Europe, the expected climate changes are likely to have a small impact on electricity prices and production. We find that each of the three partial effects examined in the present paper changes the average electricity producer price by less than 2 percent, while the net effect is an increase in the average producer price of only 1 percent. Similarly, the partial effects on total electricity production are small, and the net effect is a decrease of 4 percent.

The greatest effects of climate change are found for those Nordic countries with a large market share for reservoir hydro. In these countries total annual production increases by 8 percent, reflecting an expected increase in inflow of water. A substantial part of the increase in Nordic production is exported; climate change doubles net exports of electricity from the Nordic countries, while the optimal reservoir capacity is radically reduced.

Finally, throughout this study we have assumed a common uniform price of CO2 emissions of USD 50. A topic for future research is to analyze how different international climate agreements and climate instruments - sector neutral as well as sector-specific - may have impact on the electricity markets under future climate conditions.

References

Adam JC, Hamlet AF, Lettenmaier DP (2009) Implications of global climate change for snowmelt hydrology in the twenty-first century. Hydrol. Process. 23:962–972

Aroonruengsawat A, Auffhammer M (2009) Impacts of climate change on residential electricity consumption: evidence from billing data. Paper From: California Climate Change Center, CEC-500-2009-018-D.

Aune FR, Golombek R, Kittelsen SAC, Rosendahl KE (2008) Liberalizing European Energy Markets: An Economic Analysis. Edward Elgar.

Baxter, LW, Calandri, K (1992) Global warming and electricity demand. Energy Policy 20:233-244.

Benestad, RE (2005) Climate change scenarios for northern Europe from multi-model IPCC AR4 climate simulations. Geophys. Res. Lett. 32, L17704, doi:10.1029/2005GL023401.

Benestad RE (2008a) Heating Degree Days, Cooling Degree days and Precipitation in Europe. Analysis for the CELECT-project. met.no Report 4/2008 CLIMATE.

Benestad RE (2008b) Downscaled regional Norwegian temperature and precipitation series Analysis for Statnett and CES, met.no Report 7/2008 CLIMATE.

Benestad RE (2009) Re-calculation of local climate scenarios. met.no note 15/2009.

Bosello F, Roson R, Tol RSJ (2007) Economy-wide estimates of the implications of climate change: Sea level rise. Environ. & Resour. Econ. 37:549-571.

Carnot S, Thurston RH (editor and translator) (1890) Reflections on the motive power of heat and on machines fitted to develop that power. J. Wiley & Sons, New York.

Consensus Economics (2007) Consensus Forecasts, 2007, London: Consensus Economics.

De Cian E, Lanzi E, Roson R (2007) The impact of temperature change on energy demand: a dynamic panel analysis. Working Papers 2007.46, Fondazione Eni Enrico Mattei.

Durmayaz A, Sogut OS (2006) Influence of cooling water temperature on the efficiency of a pressurized-water reactor nuclear-power plant. Int. J. Energy Res., 30:799-810.

Eskeland GS, Mideksa TK (2009) Climate change adaption and residential electricity demand. CICERO working paper 01.

Forster H, Lilliestam J (2010) Modeling thermoelectric power generation in view of climate change. Reg. Environ. Change 10:327-338.

Gordon C, Cooper C, Senior CA, Banks H, Gregory JM, Johns TC, Mitchell JFB, Wood RA (2000) The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. Clim. Dyn.16:147-168.

Hamlet AF, Lee SY, Mickelson KEB, Elsner MM (2010) Effects of projected climate change on energy supply and demand in the Pacific Northwest and Washington State. Clim. Change 102:103-128.

Haugen JE, Iversen T (2008) Response in extremes of daily precipitation and wind from a downscaled multi- model ensemble of anthropogenic global climate change scenarios. Tellus A 60:411-426.

IEA (1998) Electricity Information 1997, OECD/IEA, Paris.

IEA (2002) Electricity Information 2002, OECD/IEA, Paris.

IEA (2008) World Energy Outlook, OECD/IEA, Paris.

IPCC (2000) Emissions Scenarios. Nakicenovic N and Swart R (eds.) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2007a) Climate Change 2007: Impacts, Adaption and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Parry ML, Canziani OF, Palutikof JP, Linden PJ van der, Hanson CE (eds.) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2007b) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Isaac M, van Vuuren DP (2009) Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. Energy Policy 37:507-521.

Kjellström E, Nikulin G, Hansson U, Strandberg G, Ullerstig A (2011) 21st century changes in the European climate: uncertainties derived from an ensemble of regional climate model simulations. Tellus A 63:24-40.

Lehner B, Czischb G, Vassoloa S (2005) The impact of global change on the hydropower potential of Europe: a model-based analysis. Energy Policy 33:839–855.

Liang X, Lettenmaier DP, Wood EF, Burges SJ (1994) A simple hydrologically based model of land surface water and energy fluxes for GSMs. J. Geophys. Res. 99:14415-14428.

Linnerud K, Mideksa TK, Eskeland GS (2009) The impact of climate change on thermal power supply. Manuscript, CICERO.

Linnerud K, Mideksa TK, Eskeland GS (2011) The impact of climate change on nuclear power supply. The Energy J. 32(1):149-168.

Lucena AFP, Szklo AS, Schaeffer R, Dutra RM (2010) The Vulnerability of Wind Power to Climate Change in Brazil, Renew. Energy 35:904-912.

Madani K, Lund JR (2010) Estimated impacts of climate warming on California's high-elevation hydropower. Clim. Change 102:521-538.

Mantua N, Tohver I, Hamlet A (2010) Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. Clim. Change doi:10.1007/s10584-010-9845-2.

Meehl GA., Stocker TF, Collins WD, et al. (2007) Global Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Mideksa TK, Kallbekken S (2010) The impact of climate change on the electricity market: A review. Energy Policy, 38:3579-3585.

Mitchell TD, Jones PD (2005) An improved method of constructing a database of monthly climate observations and associated high resolution grids. Int. J. Clim. 25:693-712.

Mohseni O, Erickson TR Stefan HG (1999) Sensitivity of stream temperatures in the United States to air temperatures projected under a global warming scenario. Water Resour. Res. 35:3723-3733.

NORDEL (2001) Annual Report 2000, Oslo: Nordel.

Perroni C, Rutherford TF (1995) ‘Regular flexibility of nested CES functions’. European Economic Review 39:335–343.

Pryor SC, Barthelmie RJ, Kjellström E (2005) Potential climate change impact on wind energy resources in northern Europe: analyses using a regional climate model. Clim. Dyn. 25:815-835.

Roeckner E, Brokopf R, Esch M, Giorgetta M, Hagemann S, Kornblueh L, Manzini E, Schlese U, Schulzweida U (2006) Sensitivity of simulated climate to horizontal and vertical resolution in the ECHAM5 atmosphere model. J. Clim. 19:3771-3791.

Røgeberg O, Andresen S, Holtsmark B (2010) International climate treaties: The case for pessimism. Clim. Law 1(1):177–197.

Sailor D, Smith M, Hart M (2008) Climate Change implications for wind power resources in the Northwest United States. Renew. Energy 33:2393-2406.

Stern N (2007) The Economics of Climate Change. The Stern Review. Cambridge University Press: Cambridge, United Kingdom and New York, USA.

Uppala SM, Kallberg PW, Simmons AJ, et al. (2005) The ERA-40 re-analysis. Quart. J. Meteo. Soc. 131:2961-3012.

Van Vliet MTH, Ludwig F, Zwolsman JJG, Weedon GP, Kabat P (2011) Global river temperatures and the sensitivity to atmospheric warming and changes in river flow. Water Resour. Res. , 47, W02544, http://dx.doi.org/10.1029/2010WR009198.

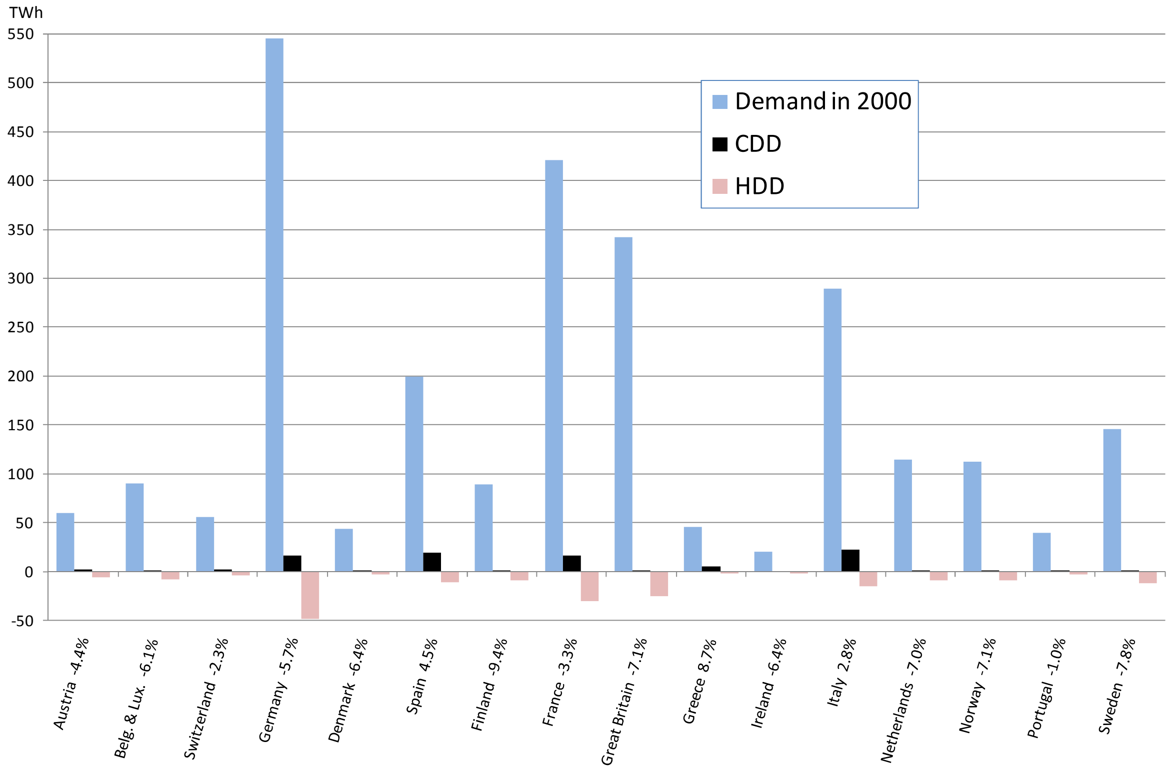

Fig. 1 Electricity demand in the base year 2000 and calculated direct changes in demand with 2085 climate because of more cooling (CDD) and less heating (HDD). Percentage numbers are total direct changes from both cooling and heating effects.

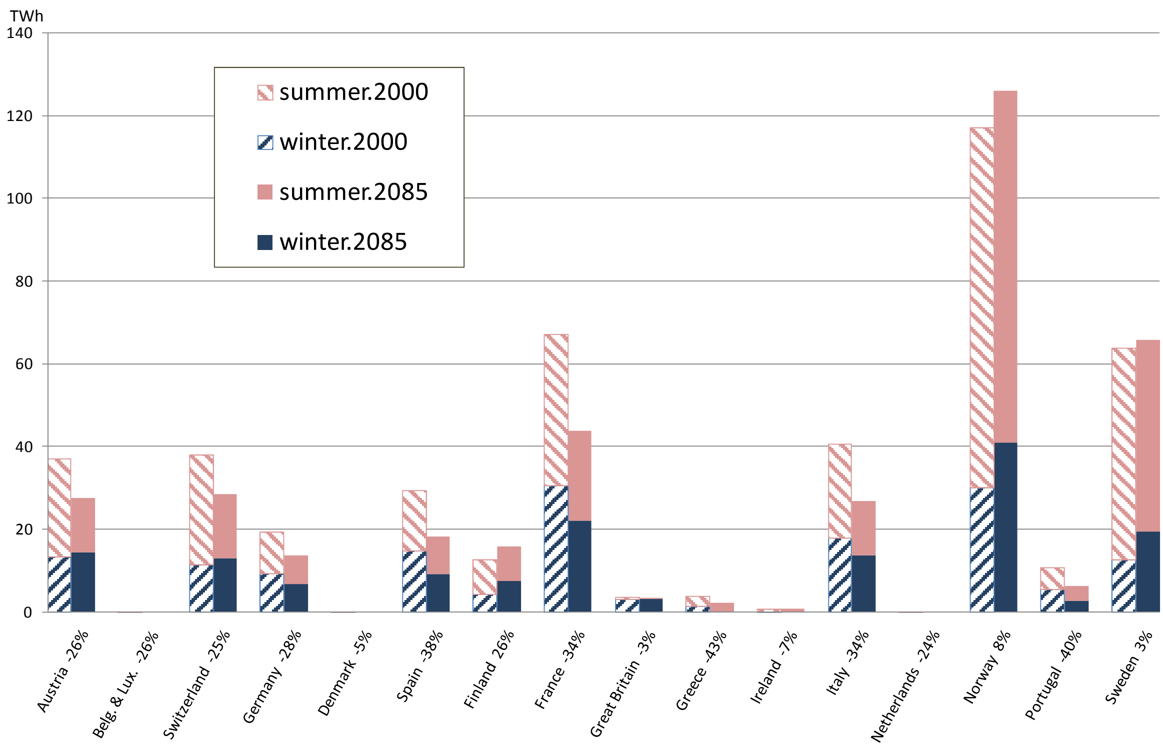

Fig. 2 Seasonal inflow in 2000 and 2085 with the 2000 power system infrastructure. Normal year production for 2000 based on Nordel (2001) and IEA (1998, 2002). Percentage numbers are total annual direct changes.

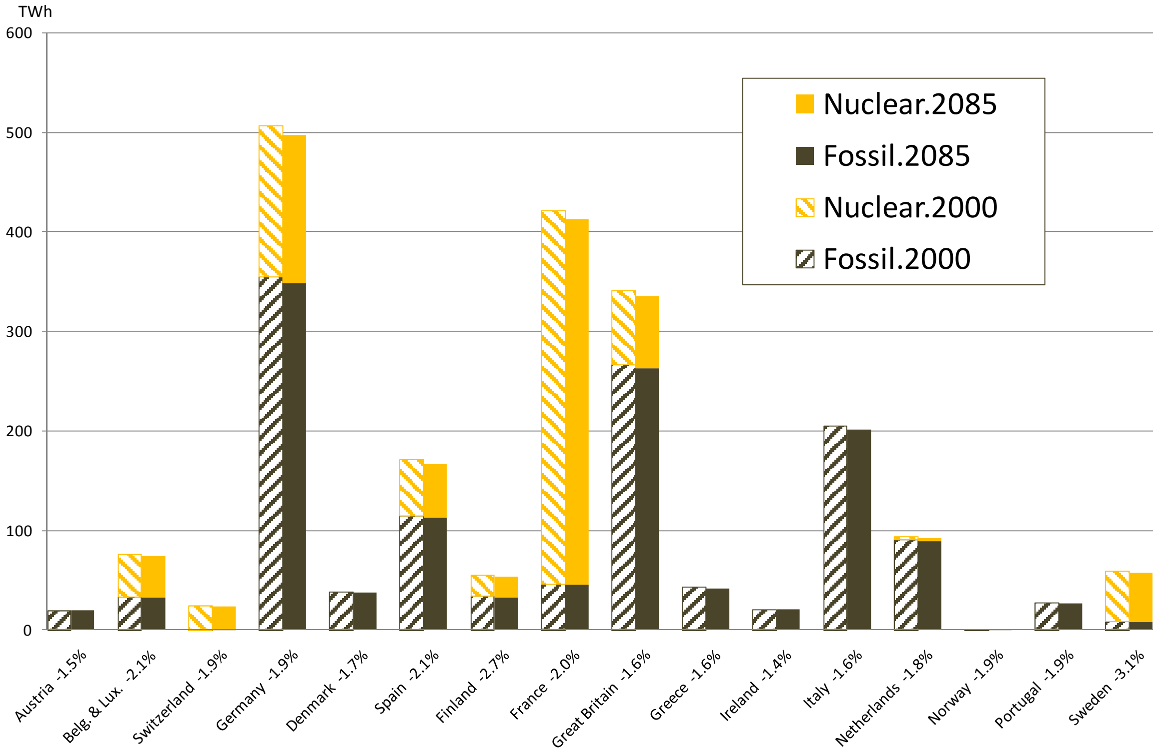

Fig. 3 Direct climate effect on thermal electricity production in 2000 and 2085 with the 2000 capacities and utilizations. Percentage numbers are direct effects for total thermal production.

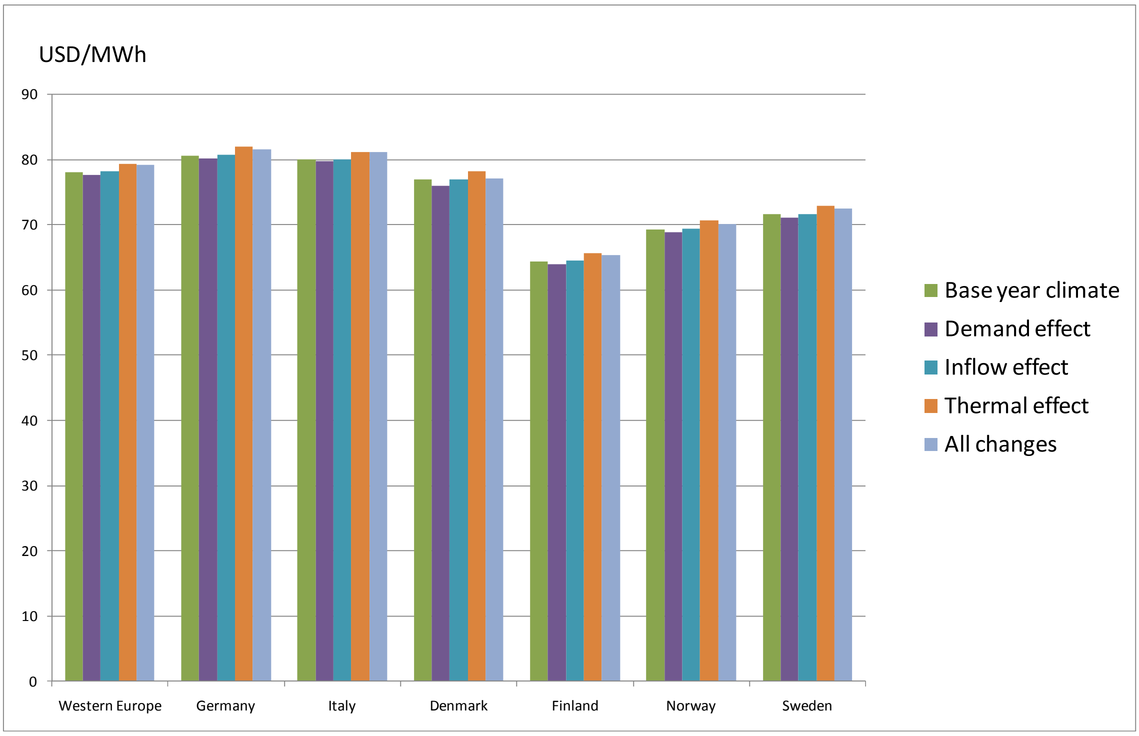

Fig. 4 Electricity producer prices in Western Europe and selected model countries in 2030 with base year climate, each partial climate effect and all climate effects.

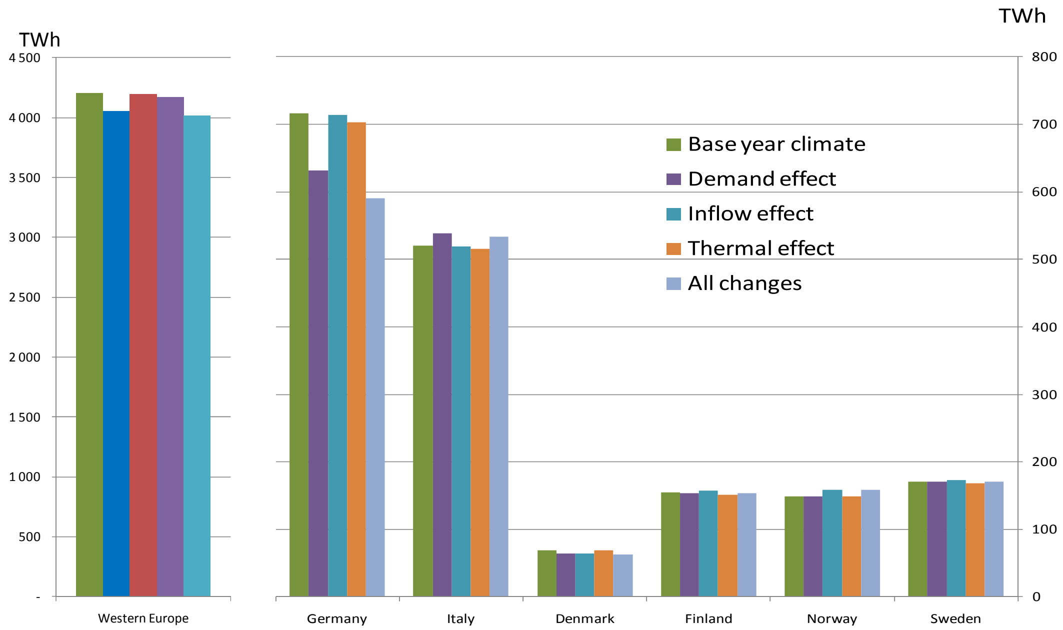

Fig. 5 Electricity production in Western Europe (left axis) and selected countries (right axis) in 2030 with base year climate, each partial climate effect and all climate effects.

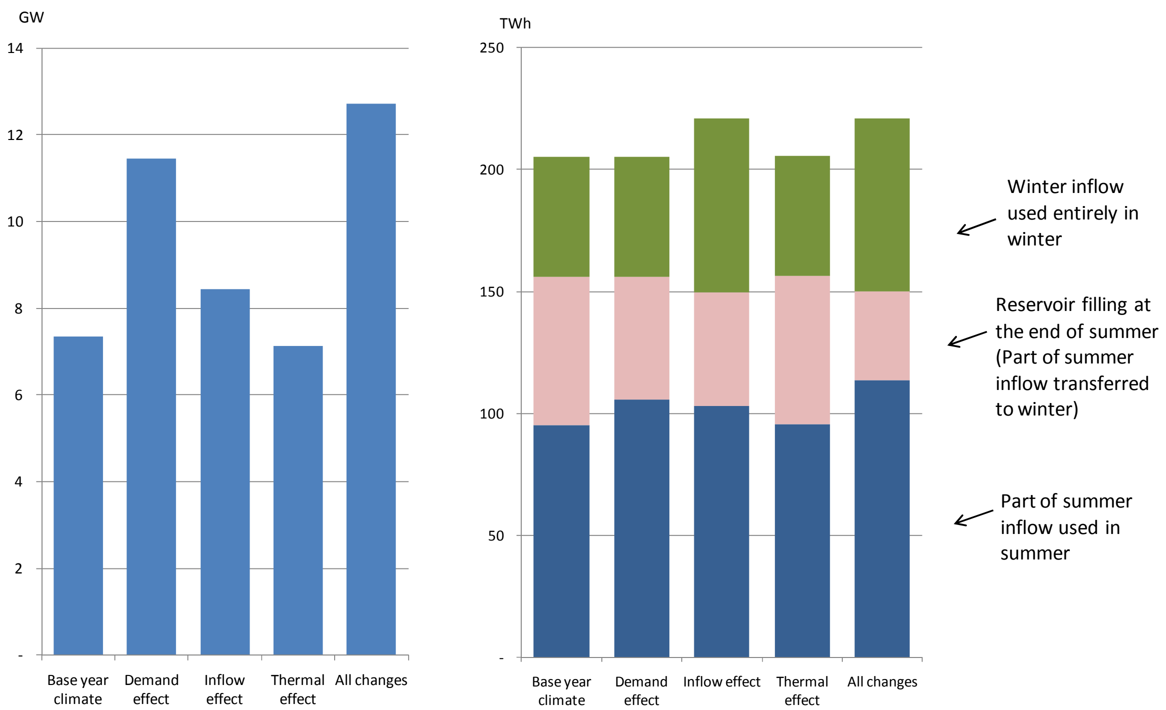

Fig. 6 Panel a: Transmission capacity between Nordic countries (Denmark, Finland, Norway and Sweden) and Continental Europe. Panel b: Hydroelectricity production in the Nordic countries by inflow and season. 2030 with base year climate, each partial climate effect and all climate effects.

Appendix A

Table A.1: Climate assumptions

	Cooling degree days (CDD)		Heating degree days (HDD)		Temperature change in C		Runoff change in pct	
	Level 2000	Change 2000-2085	Level 2000	Change 2000-2085	Summer	Winter	Summer	Winter
Austria	113	101	3032	-851	2.4	2.4	-45 %	7 %
Belg. & Lux.	37	52	2849	-817	2.7	3.1	-24 %	-27 %
Switzerland	138	121	2570	-712	2.4	2.4	-41 %	12 %
Germany	56	77	3022	-872	2.7	3.1	-30 %	-27 %
Denmark	9	14	3234	-691	2.7	3.1	-18 %	2 %
Spain	346	247	1372	-543	3.7	2.6	-37 %	-38 %
Finland	1	0	4601	-947	3.0	4.9	1 %	70 %
France	66	97	2300	-718	2.7	2.5	-40 %	-28 %
Great Britain	2	2	2734	-724	2.3	2.6	-45 %	5 %
Greece	605	311	1224	-372	2.9	2.4	-25 %	-68 %
Ireland	0	0	2883	-639	2.2	2.3	-31 %	-2 %
Italy	199	198	1801	-508	2.9	2.4	-42 %	-23 %
Netherlands	12	22	2978	-786	2.7	3.1	-25 %	-23 %
Norway	6	9	4262	-743	2.7	3.7	-2 %	36 %
Portugal	98	113	1113	-547	3.7	2.6	-31 %	-48 %
Sweden	8	10	3904	-823	3.2	4.8	-9 %	54 %
Model countries	138	121	2570	-712	2.8	3.0	-22 %	-1 %

Sources: Eskeland and Mideksa (2009) and Benestad (2009). Temperature changes for Belgium, Denmark and the Netherlands is set as Germany, for Switzerland as Austria, Greece as Italy and Portugal as Spain.

Table A.2: Market equilibrium results for 2030. Quantities in TWh and prices in USD/MWh.

	Base year climate			Demand effect			Inflow effect			Thermal effect			All changes		
	Demand	Production	price	Demand	Production	price	Demand	Production	price	Demand	Production	price	Demand	Production	price
Austria	87	106	78.3	83	103	77.7	87	102	78.5	87	113	79.5	83	109	79.8
Belg. & Lux.	127	133	79.3	118	125	78.4	127	133	79.4	126	134	80.7	117	125	80.4
Switzerland	93	98	80.2	92	96	79.9	93	98	80.5	93	97	81.4	91	96	82.0
Germany	749	717	80.6	701	631	80.2	749	714	80.7	743	703	82.0	695	591	81.6
Denmark	65	69	76.9	61	64	76.0	65	64	76.9	65	69	78.2	61	63	77.1
Spain	329	371	77.9	348	412	77.5	329	370	78.0	326	367	79.3	345	399	79.0
Finland	120	154	64.4	108	154	64.0	120	158	64.4	119	151	65.7	107	154	65.3
France	605	657	78.9	582	610	78.9	604	657	79.0	600	652	80.1	577	630	80.2
Great Britain	610	670	77.9	568	625	76.9	609	669	78.2	605	665	79.1	562	617	78.7
Greece	64	70	78.0	70	78	77.5	63	70	78.2	63	70	79.0	69	77	79.6
Ireland	38	43	75.9	36	40	76.0	38	43	76.1	38	43	76.9	36	39	77.0
Italy	490	520	79.9	507	539	79.8	490	519	80.1	486	516	81.2	503	534	81.1
Netherlands	178	198	79.5	165	180	78.4	178	195	79.7	177	197	80.9	163	178	80.4
Norway	123	149	69.3	115	148	68.8	123	159	69.4	123	149	70.6	114	159	70.1
Portugal	70	77	77.7	70	76	77.3	70	77	78.0	70	76	79.1	69	75	79.1
Sweden	150	171	71.6	137	171	71.1	150	173	71.7	149	169	72.9	136	170	72.4
Model countries	3901	4202	78.0	3761	4051	77.6	3898	4200	78.2	3869	4169	79.3	3727	4016	79.1